

# NEUTRINO ANOMALIES

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## ABSTRACT

Solar and atmospheric evidences have been established and can be explained by neutrino masses. Furthermore, other experiments claim a few unconfirmed neutrino anomalies. We critically reanalyze the  $0\nu 2\beta$ , LSND and NuTeV anomalies.

## 1. Introduction

Solar and atmospheric neutrino data show that lepton flavour is violated, and give the two *established* evidences for physics beyond the SM that we have today (the SM and its first flaw both appeared in 1968). Atmospheric, solar, reactor and  $\nu$  beam data can be fully explained by neutrino oscillations with<sup>1)</sup>

$$\begin{aligned} |\Delta m_{23}^2| &= (2.7 \pm 0.4) 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{23} = 1.00 \pm 0.04, \\ \Delta m_{12}^2 &= (7.1 \pm 0.6) 10^{-5} \text{ eV}^2, \quad \tan^2 \theta_{12} = 0.45 \pm 0.06. \end{aligned} \quad (1)$$

Although the specific dependence on neutrino path-length and energy predicted by oscillations has not yet been fully tested, present data exclude all alternative interpretations which have been proposed.

It is plausible that the physics behind present discoveries is a  $3 \times 3$  Majorana neutrino mass matrix. This is in fact what one gets adding to the SM Lagrangian higher dimensional operators (which parameterize the low-energy effects of new physics too heavy to be directly probed):

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{m_{ij}}{v^2} \frac{(L_i H)(L_j H)}{2\Lambda_L} + \dots$$

Maybe we are observing the first manifestation of a new scale of nature,  $\Lambda_L \sim 10^{14} \text{ GeV}$ , similarly to what happened in 1896, when operators suppressed by the electroweak scale  $v = 174 \text{ GeV}$  were first seen as radioactivity by Becquerel. LHC will directly explore physics at the electroweak scale in  $\sim 2008$ .

Accessing the neutrino scale could be not so fast. If the theoretical scheme outlined above is true we have seen 4 of the 9 Majorana parameters contained in  $m_{ij}$ . Planned oscillation experiments seem capable of measuring all 6 Majorana parameters which affect oscillations; neutrino-less double-beta ( $0\nu 2\beta$ ) experiments could discover violation of total lepton number and measure one more parameter.

Alternatively, neutrino experiments might discover something else which does not fit well in the above scheme. Present neutrino data show a few unconfirmed anomalies:

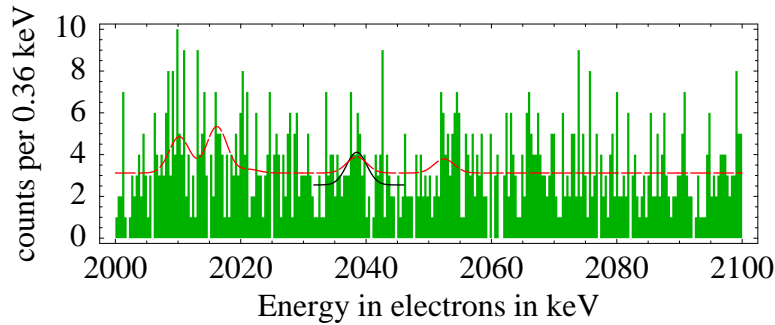


Figure 1: *Heidelberg-Moscow  $0\nu 2\beta$  data without pulse-shape-analysis.*

1. A reanalysis<sup>2)</sup> of Heidelberg-Moscow<sup>3)</sup>  $0\nu 2\beta$  data claims  $|m_{ee}| \sim \text{eV}$ .
2. LSND<sup>4)</sup> claims  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  with small  $\theta$  and  $\Delta m^2 \sim \text{eV}^2$ .
3. NuTeV<sup>5)</sup> claims  $\nu_\mu/\text{iron}$  couplings  $\sim 1\%$  away from the SM.
4. The apparent observation of cosmic rays above the GZK cut-off might be related to neutrino masses ( $\nu_{\text{UHE}} \nu_{\text{CMB}} \rightarrow Z$  with  $m_\nu \sim \text{eV}$ ) or to problems with energy calibration.

We discuss possible interpretations of the first three hints (within the SM and beyond) and their signals. Since this is not established physics, we unavoidably touch controversial issues: I try to present what seems true to me without hiding problems and signalling the most controversial points. Hopefully future data will lead to a definite conclusion, maybe confirming one or more of these anomalies.

## 2. Heidelberg-Moscow

Neutrino masses distort the end-point spectrum of  $\beta$  decays. From studies of  $^3\text{H} \rightarrow ^3\text{He} e \bar{\nu}_e$  the MAINZ experiment sets the 95% CL bound  $m_\nu < 2.2 \text{ eV}$  (TROITSK has a similar sensitivity)<sup>6)</sup>.

Some nuclei cannot  $\beta$ -decay. For example  $^{76}_{32}\text{Ge}$  cannot  $\beta$ -decay to  $^{76}_{33}\text{As}$  that is heavier, so it  $\beta\beta$  decays as  $^{76}_{32}\text{Ge} \rightarrow ^{76}_{34}\text{Se} e e \bar{\nu}_e \bar{\nu}_e$  ( $Q = 2038.6 \text{ keV}$ ). Various experiments have observed this and other analogously rare SM processes. If neutrinos have Majorana masses, the  $L$ -violating decay  $^{76}_{32}\text{Ge} \rightarrow ^{76}_{34}\text{Se} e e$  has a non zero amplitude proportional to  $m_{ee}$ , the  $ee$  entry of the Majorana neutrino mass matrix. The experimental signal is two electrons with total kinetic energy equal to the  $Q$  value of the decay. A reanalysis<sup>2)</sup> of the Heidelberg-Moscow (HM) data<sup>3)</sup> shown in fig. 1 claimed a  $(2.2 \div 3.1)\sigma$  evidence for  $0\nu 2\beta$ . To properly understand HM data one needs to know

that the  $0\nu 2\beta$  signal is a peak at  $Q = 2038.6$  keV with known width,  $\sigma_E \approx 1.6$  keV given by the energy resolution, emerging over the  $\beta\beta$  and other backgrounds, which are not well known. The evidence in<sup>2)</sup> was claimed assuming

$$\text{data} = (\text{flat background}) + (0\nu 2\beta \text{ peak})$$

and distinguishing the two components through a spectral analysis, restricted to data in a small search window around  $Q$  with few  $\sigma_E$  size. The continuous line in fig. 1 shows the resulting best-fit: we obtain a  $2.0\sigma$  evidence. The evidence depends on the choice of the window size: we have chosen the window where data mostly look like a peak, maximizing the evidence for peak<sup>a</sup>. Employing a large window (which would be the right choice, if the background were really flat) the evidence decreases to  $0.8\sigma$ .

Furthermore, the HM spectrum contains a few other apparent peaks, some around the energies of faint  $\gamma$  lines of  $^{214}\text{Bi}$  (a radioactive impurity present in the apparatus). Fitting all data using all the information we have

$$\text{data} = (\text{Bi peaks}) + (\text{cte background}) + (0\nu 2\beta \text{ peak})$$

we find a  $1.2\sigma$  evidence<sup>b</sup> as illustrated by the dashed line in fig. 1. Other reanalyses performed along similar lines and precisely described by their authors find  $1.1\sigma$ <sup>10)</sup>,  $1.46\sigma$ <sup>9)</sup>, less than  $1\sigma$ <sup>11)</sup> (these authors combine HM<sup>3)</sup> and IGEX<sup>12)</sup> data. Both experiments use  $^{76}\text{Ge}$  with a similar energy resolution and background level. IGEX has about 5 times less statistic and finds a slight deficit of events around the  $0\nu 2\beta$   $Q$  value, where HM finds a slight excess). In conclusion, the hint for  $0\nu 2\beta$  is not statistically significant. HM data would contain an evidence for  $0\nu 2\beta$  if one could show that the background around  $Q$  is lower than what fig. 1 seems to indicate.

We now shift topic and study what oscillation data imply on  $m_{ee}$ , assuming 3 neutrinos with Majorana masses. Therefore we rewrite  $|m_{ee}|$  in terms of mixing angles  $\theta_{ij}$ , neutrino masses  $m_{1,2,3}$  and Majorana phases  $\alpha, \beta$

$$|m_{ee}| = \left| \sum_i V_{ei}^2 m_i \right| = \left| \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{i\alpha} \sin^2 \theta_{12}) + m_3 e^{i\beta} \sin^2 \theta_{13} \right|.$$

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<sup>a</sup>The authors of<sup>2)</sup> claim that the restriction in the window search is not a critical arbitrary choice, in apparent disagreement with<sup>7)</sup>. The claim in<sup>2)</sup> refers to a fit of an average sample of *simulated* data (generated under some assumption), while ref.<sup>7)</sup> finds that the restriction in the window search turns out to be a critical arbitrary choice when analyzing the *real* data.

<sup>b</sup>The tentative identification of some of the spurious peaks in the HM spectrum with faint  $^{214}\text{Bi}$   $\gamma$  lines proposed in<sup>2)</sup> had been criticized in<sup>7,8)</sup>, because their intensity appeared incompatible with the intense  $^{214}\text{Bi}$   $\gamma$  lines, clearly present in HM data. This issue has been clarified and the relative intensities are now compatible within  $2\sigma$ . The initial estimate has been corrected by a factor of 6 (as first noticed in footnote 9 of a revised version of<sup>7)</sup>, there is a trivial normalization error in the published HM data<sup>3)</sup>) times another  $\mathcal{O}(\text{few})$  factor related to pile-up effects (computed assuming that  $^{214}\text{Bi}$  is located in the copper part of the detector)<sup>9)</sup>.

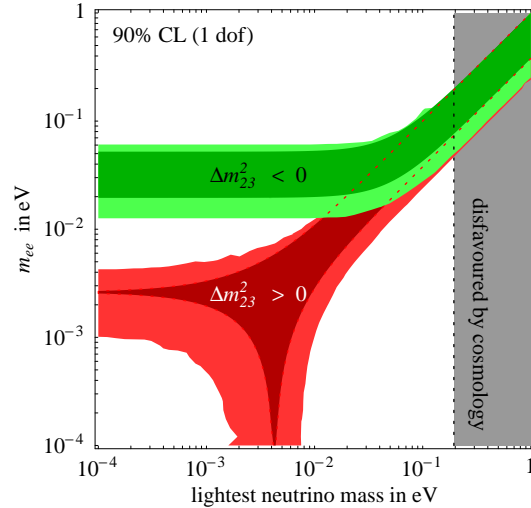


Figure 2:  $|m_{ee}|$  range allowed by all oscillation data.

Using a global fit of all oscillation data<sup>15)</sup>, we plot in fig. 2 the  $|m_{ee}|$  range at 90% CL as function of the lightest neutrino mass<sup>7)</sup>. The darker regions in fig. 2 show the remaining uncertainty in  $|m_{ee}|$  due to the Majorana phases that we would achieve if the present best-fit values of oscillation parameters in eq. (1) were confirmed with infinite precision (we are assuming  $\theta_{13} = 0$ ).

Combining the HM<sup>3)</sup> bound on  $|m_{ee}|$  with solar data which point to less than maximal mixing  $\theta_{12}$  one can derive an interesting bound on the mass  $m_\nu$  of almost-degenerate neutrinos<sup>7)</sup>

$$m_\nu < 1.0 \text{ (1.5) } h \text{ eV} \quad \text{at 90 (99\%) CL.} \quad (2)$$

The factor  $h \approx 1$  parameterizes the uncertainty in the  $0\nu 2\beta$  nuclear matrix element (see sect. 2.1 of ref.<sup>7)</sup>). Our bound holds under the untested assumption that neutrinos are Majorana particles, and can be evaded adding e.g. Dirac neutrino masses. Cosmology gives a tighter limit<sup>13,14)</sup>,  $m_\nu < 0.23 \text{ eV}$  at 95% CL, under the untested assumption that a minimal inflationary model describes structure formation and can be evaded by e.g. compensating  $\nu$  free-streaming with a primordial tilt in the power spectrum.

In the future, the sensitivity of  $0\nu 2\beta$  experiments to neutrino masses should improve more significantly than cosmology and  $\beta$ -decay. Fig. 2 shows that planned  $0\nu 2\beta$  experiments, which could reach a sensitivity in  $|m_{ee}|$  of few meV, should see a signal if the spectrum of neutrinos is ‘inverted’ (i.e.  $\Delta m^2_{23} < 0$ ) or ‘quasi degenerate’ (i.e.  $\min m_i \gtrsim 0.05 \text{ eV}$ ).

model and number of free parameters	$\Delta\chi^2$	mainly incompatible with	main future test
ideal fit (no known model)	0		?
$\Delta L = 2$ decay $\bar{\mu} \rightarrow \bar{e}\bar{\nu}_\mu\bar{\nu}_e$	6	KARMEN	TWIST
$3 + 1 : \Delta m_{\text{sterile}}^2 = \Delta m_{\text{LSND}}^2$	9	6 + 9? BUGEY + cosmology?	MINIBOONE
3 $\nu$ and $\mathcal{CPT}$ (no $\Delta \bar{m}_{\text{sun}}^2$ )	10	KamLAND	KAMLAND
3 $\nu$ and $\mathcal{CPT}$ (no $\Delta \bar{m}_{\text{atm}}^2$ )	10	SK atmospheric	$\bar{\nu}_\mu$ LBL?
normal 3 neutrinos	5	LSND	MINIBOONE
$2 + 2 : \Delta m_{\text{sterile}}^2 = \Delta m_{\text{sun}}^2$	9	SNO	SNO
$2 + 2 : \Delta m_{\text{sterile}}^2 = \Delta m_{\text{atm}}^2$	9	50 SK atmospheric	$\nu_\mu$ LBL

Table 1: Interpretations of solar, atmospheric and LSND data, ordered according to the quality of their global fit. A  $\Delta\chi^2 = n^2$  roughly signals an incompatibility at  $n$  standard deviations.

### 3. LSND

Both the LSND<sup>4)</sup> and KARMEN<sup>16)</sup> experiments study  $\bar{\nu}_\mu$  obtained from  $\mu^+$  decay at rest, that therefore have a well known energy spectrum up to 52.8 MeV. The search for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  is performed using the detection reaction  $\bar{\nu}_e p \rightarrow n e^+$ , that has a large cross section. The detectors try to identify both the  $e^+$  and the  $n$  (via the 2.2 MeV  $\gamma$  emitted when the neutron is captured by a proton). The neutrinos travel for  $L \approx 30$  m in LSND and  $L \approx 17.5$  m in KARMEN.

LSND finds an evidence for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ , that ranges between 3 to  $7\sigma$  depending on how data are analyzed. This happens because LSND has a poor signal/background ratio: choosing the selection cuts as in<sup>17)</sup> the LSND sample contains 1000 background events and less than 100 signal events, distinguished only on a statistical basis. The statistical significance of the LSND signal depends on how cuts are chosen, and it is crucial that all sources of background have been correctly computed. The main backgrounds are cosmic rays and  $\nu_e$  misidentification. The final LSND result  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.6 \pm 0.8) 10^{-3}$  can be explained by oscillations with  $\Delta m^2 \gtrsim 0.1 \text{ eV}^2$  (see<sup>4,17)</sup> for the precise range).

KARMEN is cleaner than LSND but has a few times less statistics and shorter baseline. KARMEN finds 15 events versus an expected background of 15.8 events, excluding the part of the  $(\Delta m^2, \theta)$  range suggested by LSND with larger  $\Delta m^2 \gtrsim 2 \text{ eV}^2$ , while at smaller  $\Delta m^2$  the longer path-length makes LSND more sensitive than KARMEN. The LSND anomaly is being tested as  $\nu_\mu \rightarrow \nu_e$  by the MINIBOONE experiment, which has quite different systematics.

If confirmed, the LSND anomaly will require a significant revision of the standard

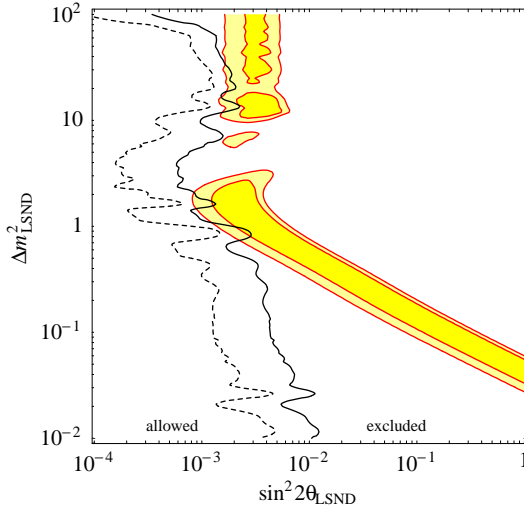


Figure 3: The LSND region in the  $(\sin^2 2\theta_{\text{LSND}}, \Delta m^2_{\text{LSND}}/\text{eV}^2)$  plane at 90% and 99% CL (shaded area), compared with the 90% (dashed line) and 99% CL (continuous line) exclusion bounds from other oscillation data computed in a 3+1 oscillation scheme.

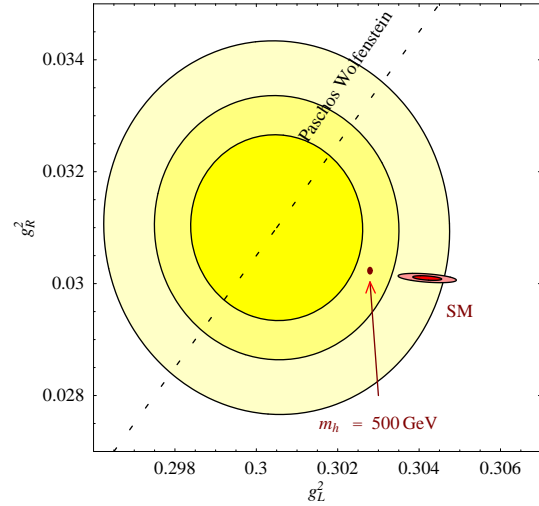


Figure 4: The SM prediction for  $(g_L^2, g_R^2)$  at 68, 99% CL compared with the NuTeV determination at 68, 90, 99% CL (big ellipses). The NuTeV central value moves along the PW line using different sets of parton distribution functions that assume  $s = \bar{s}$  and  $u^p = d^n$ .

picture. In fact, oscillations between the three SM neutrinos are described by two independent squared neutrino mass differences, allowing to explain only two of the three atmospheric, solar and LSND neutrino anomalies as oscillations.

One possible global explanation of the three anomalies is that an extra sterile neutrino generates one of them. The sterile neutrino can be used to generate either the LSND or the solar or the atmospheric anomaly, or some combination of them. Only the first possibility is now compatible with data<sup>18,19)c</sup>. According to this possibility, named ‘3+1’ oscillations in the jargon,  $\nu_\mu \rightarrow \nu_e$  oscillations at the

<sup>c</sup>The other possibilities would remain strongly disfavoured even if possible reasons for being more cautious would apply. R. Foot, *hep-ph/0210393* suggests that theoretical errors might have been underestimated in analyses of NC enriched SK data which disfavour atmospheric sterile oscillations. Furthermore, bounds on the sterile component involved in solar oscillations would be weakened if solar models underestimate the  $^8\text{B}$  flux. H. Pas et al., *hep-ph/0209373* suggest that adjusting all the small mixing angles allowed by a  $4\nu$  framework might weaken the bounds.

R. Foot, *hep-ph/0210393* suggests that scenarios with  $\nu_\mu \rightarrow \nu_s$  atmospheric oscillations provide a global fit of all neutrino data with  $\chi^2/\text{dof} \approx 291/276$ , which is acceptable. This is true, but the goodness-of-fit (gof) test based on the value of the total  $\chi^2$  is inefficient when  $\text{dof} \gg 1$ : it may assign an acceptable gof probability to a solution which is already excluded. This issue was discussed in the context of analyses of solar data in<sup>15)</sup> and can be exemplified by recalling that, according to global fits of solar and KamLAND data<sup>15)</sup>, the LOW solution has been excluded but its naïve gof is still acceptable (presently it has  $\chi^2/\text{dof} = 89/91$ ).

LSND frequency proceed through  $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ , so that the effective  $\nu_e \nu_\mu$  mixing angle at the LSND frequency is  $\theta_{\text{LSND}} \approx \theta_{es} \theta_{\mu s}$ . Due to this ‘product rule’<sup>20)</sup> the LSND anomaly somewhat conflicts with bounds on  $\theta_{es}$  and  $\theta_{\mu s}$  from  $\nu_e$  and  $\nu_\mu$  disappearance experiments. The situation is quantitatively summarized in table 1 and fig. 3. The part of the LSND region still marginally compatible with other oscillation experiments has  $\Delta m_{\text{LSND}}^2 \sim \text{eV}^2$  and  $\sin^2 2\theta_{\mu s} \sim 0.2$  (for more details see<sup>18,19)</sup>).

Furthermore, cosmology disfavors such 3+1 interpretation of the LSND anomaly for two different reasons: because 3+1 oscillations thermalize a fourth sterile neutrino, and because it is heavy. Since both issues are still controversial, we now try to summarize what cosmology is really telling.

Massive neutrinos make galaxies less clustered: recent global fits of cosmological data find  $m_\nu \lesssim 1 \text{ eV}$  (the analysis performed by the WMAP team gives the strongest bound<sup>13)</sup>, criticized by<sup>14)</sup> who find appropriate a more conservative treatment of data at small scale and of bias). The bound on  $m_\nu$  gets slightly relaxed if there are  $N_\nu = 4$  thermalized neutrinos<sup>14)</sup>. 3+1 oscillations indeed thermalize  $N_\nu = 4$  neutrinos before the big-bang nucleosynthesis (BBN) epoch, and  $N_\nu = 4$  seems not compatible with BBN. Assuming standard cosmology, the dominant bound on  $N_\nu$  comes from the BBN prediction for the  $^4\text{He}$  primordial abundance, using as input the baryon asymmetry extracted from CMB data. A global fit of cosmological data gives  $N_\nu = 2.6 \pm 0.2$ <sup>14)</sup>, which apparently excludes  $N_\nu = 4$  and even disfavors  $N_\nu = 3$ . One can avoid these conclusions by enlarging the error on the  $^4\text{He}$  primordial abundance, since its determination is still controversial. In table 1 we tried to make a quantitative statement, which can be criticized telling either that it underestimates or that it overestimates the impact of cosmology.

When data started disfavoring interpretations of the LSND anomaly based on sterile neutrinos, other more exotic solutions were proposed. None of them can fully reconcile of data.

Since solar and atmospheric oscillations have been established in neutrinos but not yet in anti-neutrinos, one can try to explain all anomalies assuming a CPT-violating neutrino spectrum. The larger  $\Delta m^2$  between  $\bar{\nu}_{e,\mu,\tau}$  is used to explain the LSND anomaly, and the smaller  $\Delta m^2$  could be in the atmospheric or in the solar range, at the price of sacrificing some solar<sup>21)</sup> or atmospheric<sup>18,22)</sup> anti-neutrino data. These CPT-violating spectra are now somewhat disfavoured, as quantitatively summarized in table 1. KamLAND will soon precisely probe CPT in the solar sector. Doing the same in the atmospheric sector would require a dedicated  $\bar{\nu}_\mu$  long-baseline (LBL) experiment or a dedicated atmospheric experiment such as MONOLITH.

The LSND anomaly might be produced by a non standard ( $\Delta L = 2!$ ) decay mode  $\bar{\mu} \rightarrow \bar{\nu}_e \bar{e} \bar{\nu}$ <sup>23)</sup>. It affects electroweak precision data and the  $\bar{e}$  spectrum in  $\bar{\mu}$  decays.

The latter signal is under test at TWIST. This  $\bar{\mu}$  decay interpretation of the LSND anomaly is disfavoured by KARMEN, since unlike oscillations it does not exploit the fact that LSND has a longer path-length<sup>18)</sup>; a more precise quantitative statement than the one in table 1 will be possible if LSND will analyze their data in this context.

In conclusion, the recent experimental progress has disfavoured all proposed interpretations of the LSND anomaly. Some of them are not yet excluded, and will be tested by future experiments, as summarized in table 1.

#### 4. NuTeV

The NuTeV collaboration<sup>5)</sup> reported a  $\sim 3\sigma$  anomaly in the NC/CC ratio of deep-inelastic muon-neutrino/nucleon scattering. The effective  $\nu_\mu$  coupling to left-handed quarks is found to be about 1% lower than the best fit SM prediction.

The NuTeV collaboration sent both a  $\nu_\mu$  and a  $\bar{\nu}_\mu$  beam on an iron target. Scattering events were detected by a calorimeter. The muon produced in CC events gives a long track, while the hadrons in NC events give a short track. NuTeV statistically distinguishes NC from CC events putting a cut on the track length. The ratios of neutral-current (NC) to charged-current (CC) deep-inelastic neutrino-nucleon scattering total cross-sections,  $R_\nu$  and  $R_{\bar{\nu}}$ , are free from the uncertainties on the neutrino fluxes and contain the most interesting information. We recall the tree-level SM prediction for these quantities. Including only first generation quarks, for an isoscalar target, and to leading order,  $R_\nu$  and  $R_{\bar{\nu}}$  are given by

$$R_\nu = \frac{\sigma(\nu\mathcal{N} \rightarrow \nu X)}{\sigma(\nu\mathcal{N} \rightarrow \mu X)} = g_L^2 + r g_R^2 \quad R_{\bar{\nu}} = \frac{\sigma(\bar{\nu}\mathcal{N} \rightarrow \bar{\nu} X)}{\sigma(\bar{\nu}\mathcal{N} \rightarrow \bar{\mu} X)} = g_L^2 + \frac{1}{r} g_R^2,$$

where

$$r \equiv \frac{\sigma(\bar{\nu}\mathcal{N} \rightarrow \bar{\mu} X)}{\sigma(\nu\mathcal{N} \rightarrow \mu X)} = \frac{3\bar{q} + q}{3q + \bar{q}} \sim \frac{1}{2}$$

and  $q = (u + d)/2$  and  $\bar{q}$  denote the fraction of the nucleon momentum carried by quarks and antiquarks, respectively. In this approximation the single parameter  $r$  accounts for the uncertain QCD dynamics and, after including various significant but ‘trivial’ corrections<sup>d</sup>, the NuTeV data can be presented as a measurement of  $g_L^2$  and  $g_R^2$ , the NC/CC ratio of effective  $\nu_\mu q_L$  and  $\nu_\mu q_R$  couplings, predicted by the SM to be

$$g_L^2 = \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W, \quad g_R^2 = \frac{5}{9} \sin^4 \theta_W.$$

The big ellipse in fig. 4 is the NuTeV result, obtained summing in quadrature statistical and systematic uncertainties.  $g_L$  is found to be  $\sim 3\sigma$  below its SM prediction.

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<sup>d</sup>Cuts, QED and electroweak corrections, iron contains more neutrons than protons, the charm threshold,... In principle, only a careful job is needed to include all these effects correctly.



The difference of the effective couplings  $g_L^2 - g_R^2$  (‘Paschos–Wolfenstein ratio’<sup>24)</sup>) does not depend on  $r$

$$R_{\text{PW}} \equiv \frac{R_\nu - r R_{\bar{\nu}}}{1 - r} = \frac{\sigma(\nu\mathcal{N} \rightarrow \nu X) - \sigma(\bar{\nu}\mathcal{N} \rightarrow \bar{\nu} X)}{\sigma(\nu\mathcal{N} \rightarrow \ell X) - \sigma(\bar{\nu}\mathcal{N} \rightarrow \bar{\ell} X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2 \theta_W. \quad (3)$$

The value of  $R_\nu$  measured at NuTeV is consistent with previous experiments, such as CCFR<sup>25)</sup>. Unlike CCFR, NuTeV has two separate  $\nu_\mu$  and  $\bar{\nu}_\mu$  beams: this is the main improvement because, under the above assumptions, allows to get rid of the unprecisely known partonic structure of the nucleon using  $R_{\text{PW}}$ . The NuTeV value of  $R_{\text{PW}}$  is  $\sim 3\sigma$  below its SM prediction.

Doing precision physics with iron is a delicate task. NLO QCD corrections have not taken into account by the NuTeV collaboration. They cancel out in the ideal  $R_{\text{PW}}$  observable<sup>26)</sup> and therefore probably cannot explain the NuTeV anomaly (caution is needed because what NuTeV really measures is a few 10% different from the total cross sections which appear in the ideal PW observable).

Parton distributions  $q(x)$  are extracted from global fits, usually performed under two simplifying assumptions:  $s(x) = \bar{s}(x)$  and  $u^p(x) = d^n(x)$ . These approximation could fail, at the level of precision reached by NuTeV. In presence of a momentum asymmetry  $q^- = \int_0^1 x[q(x) - \bar{q}(x)]dx$  the ideal PW observable shifts as

$$R_{\text{PW}} = \frac{1}{2} - \sin^2 \theta_W + (\text{EW corrections}) + (1.3 + \text{QCD corrections})(u^- - d^- - s^-).$$

Both  $u^- - d^-$  (isospin violation) and  $s^-$  (strange momentum asymmetry) might produce the NuTeV anomaly compatibly with other data.

Isospin violating effects of order  $u^- - d^- \sim (m_u - m_d)/\Lambda_{\text{QCD}}$  could reconcile NuTeV with the SM compatibly with all other available data. Some detailed computations performed replacing QCD with more tractable phenomenological models suggest that, due to cancellations, isospin-violating effects are somewhat too small<sup>27)</sup>. It is not clear if a QCD computation would lead to the same conclusion.

The theoretical situation concerning  $s^-$  is similar. Since a nucleon contains 3 quarks (rather than three antiquarks) one expects that  $s$  and  $\bar{s}$  carry comparable (but not equal) fractions of the total nucleon momentum. Non perturbative fluctuations like  $p \leftrightarrow K\Lambda$  are expected to give  $s$  harder than  $\bar{s}$  since  $K$  is lighter than  $\Lambda$ . Indeed  $s^- > 0$  could explain the NuTeV anomaly. Some model computations suggest that  $s^-$  is too small<sup>28)</sup>, but again it is not clear how reliable they are. The  $s^-$  issue can also be addressed relying on experimental data. The global parton fit in<sup>29)</sup> found a hint for a  $s^-$  of the desired sign and magnitude. However, a  $s^-$  with the opposite sign was suggested by an analysis of charm production data, obtained and analyzed by

the NuTeV collaboration<sup>30)</sup>. This analysis is unreliable for various reasons listed in a note added to<sup>26)</sup>. Charm production data probe the strange content of the nucleon in a powerful way, but we are not able of reliably guessing what they imply for  $s^-$ . It seems worth performing a professional analysis, even if this not an easy task.

Finally, nuclear effects<sup>31)</sup> could affect  $R_\nu$  and  $R_{\bar{\nu}}$ , but only at low momentum transfer and apparently not in a way that allows to reconcile NuTeV data with the SM<sup>30)</sup>. In part, nuclear effects are automatically included in the NuTeV analysis, based on their own parton distributions obtained fitting only iron data.

In conclusion, testing and eventually excluding such SM ‘systematic effects’ which can produce the NuTeV anomaly seems to be a difficult job<sup>e</sup>. Therefore, it is useful to speculate about possible new physics interpretations which might have cleaner signatures. Unfortunately, no particularly compelling new physics with distinctive signatures has been found. The problem is that charged lepton couplings agree with the SM and have been measured about 10 times more accurately than neutrino couplings. Proposals which overcome this problem look exotic, while more plausible possibilities work only if one deals with constraints in a ‘generous’ way or introduces and fine-tunes enough free parameters. For example, mixing the  $Z$  boson with an extra  $Z'$  boson modifies NC neutrino couplings, but also NC couplings of charged leptons ( $\ell_L$  and  $\nu$  are unified in the same  $SU(2)_L$  doublet). New physics that only affects the gauge boson propagators cannot fit the NuTeV anomaly due to the same constraints. Neutrino oscillations do not work. A reduction of neutrino couplings due to a  $\sim 1\%$  mixing with sterile singlets does not work, because CC neutrino couplings have been too precisely tested by  $\mu$  decay together with precision data. Combinations of the above effects with enough unknown parameters can work<sup>f</sup>. The new physics could either be heavy with sizable couplings (so that future colliders should see it) or light with small couplings (e.g. a  $Z'$  with few GeV mass and negligible mixing with the  $Z$ ).

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<sup>e</sup>Using a different terminology, this means that in the meantime in view of ‘additional uncertainties’ NuTeV is not inconsistent with the SM.

<sup>f</sup>For example, mixing with a sterile singlet together with a heavy higgs fits all data if one also assumes that some extra unspecified new physics affects  $M_W$  and therefore ignores this measurement<sup>32)</sup>. A failure of the SM fit of electroweak data would support the case for new physics, but at the moment we do not see any convincing problem.

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